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A DISCRETE NONLINEAR SPECTRAL MODEL FOR OCEAN WAVE PREDICTION, --ETC(U)
APR 82 J H ALLENDER, M LYBANON

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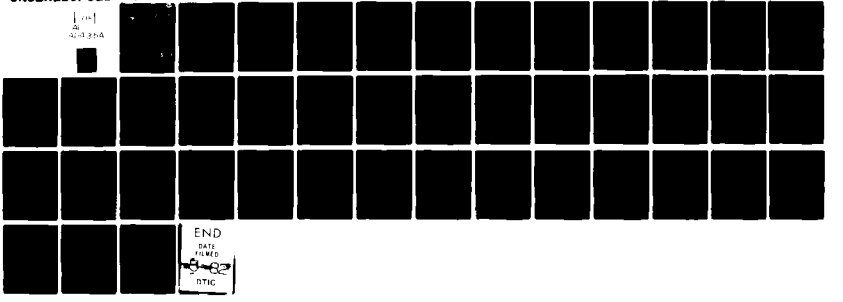

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Naval Ocean Research and
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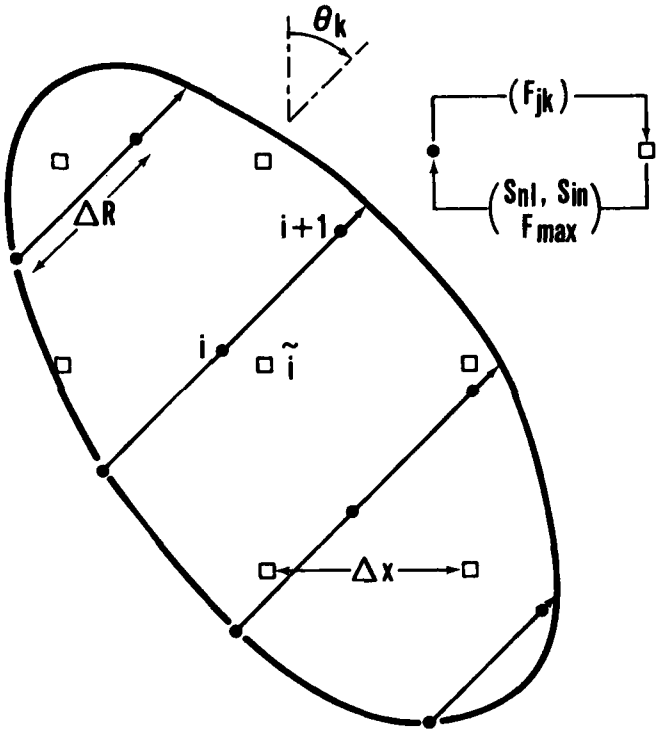
NSTL Station, Mississippi 39529

A Discrete Nonlinear Spectral Model for Ocean Wave Prediction, Description of Computer Program



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M. Lybanon

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Ocean Science and Technology Laboratory

April 1982

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ABSTRACT

An improved spectral model for ocean wave prediction is described. The present model, a modified version of the original model by Barnett et al. (contract N62306-68-C-0285, U.S. Naval Oceanog. Off., 1969) includes an improved representation for weak, nonlinear, wave-wave interactions that depends on spectral shape and prescribes atmospheric input that is consistent with measurements by Snyder et al. (J. Fl. Mech., 102, 1-59, 1981). The limiting form of the spectrum is defined as a Pierson-Moskowitz spectrum with a variable saturation range parameter. Some additional constraints are also used to obtain stable spectra because there is, in effect, a mismatch between the numerous degrees of freedom of the two-dimensional wave spectrum and the level of sophistication used to represent the physical processes affecting wave growth.

The focus of the present note is on the wave model computer program. The note is organized for someone wanting to implement the program. Hence, top-level flow charts, user instructions, and tape output formats are given. In addition, a detailed description of the numerical method is included.

ACKNOWLEDGEMENTS

T.P. Barnett of Scripps Institution of Oceanography developed the empirical orthogonal functions used to represent the nonlinear transfer and conducted many numerical experiments pointed toward improving the model. T.P. Barnett is thanked for being an enthusiastic collaborator through the entire project. P.M. Yager assisted with model implementation in the early phases of the project. K. and S. Hasselmann of Max Planck Institut kindly provided the theoretical calculations for nonlinear transfer that were used to develop our empirical functions. Joyce Ford is thanked for typing the manuscript.

CONTENTS

TABLES

A DISCRETE NONLINEAR SPECTRAL MODEL FOR OCEAN WAVE PREDICTION, DESCRIPTION OF COMPUTER PROGRAM

I. INTRODUCTION

Predicting the ocean surface wave spectrum is a formidable task. First, a knowledge of the temporally- and spatially-varying winds over the domain of interest is required. Second, a model that uses these winds to predict the wave spectrum, which depends on space, time, frequency, and direction, is needed. Finally, computer graphics to display model results are highly desirable.

For the present note the winds are regarded as known. Our primary purpose is to describe in considerable detail the computer program that was developed in the present study. The original model was described by Barnett (1968) and Barnett et al. (1969). The rationale for the overall model is given in Allender et al. (1982). A larger perspective on wave prediction, as well as intercomparisons among the present and other models in ideal situations, can be found in Hasselmann et al. (1982). The remainder of this note is organized for someone who wants to use the model program, not someone who wants to learn about wave prediction in general. The unfamiliar reader should therefore consult the preceding references for the necessary background information. In the final section of the note we take a somewhat broader perspective by describing some of the pitfalls we found, future changes for this model, and possible changes for wave prediction models in general.

II. DESCRIPTION OF COMPUTER PROGRAM

A. WAVESET

WAVESET defines the problem geometry - the time step, spatial grid, discrete frequencies and directions, boundaries, and ray families. These quantities

influence the rays in two ways: (1) in principle it is possible to have a different family of parallel rays at each direction for each frequency (different in terms of spacing and arrangement), and (2) spacing of points along the rays is based on the distance $C_g \Delta t$, where C_g is the group velocity, a function of frequency , and Δt is the time step. Ray point spacing is an integral multiple (possibly 1) of this distance. The multiplier can be specified independently for each frequency. A different set of ray directions can be specified for each frequency.

In accordance with the characteristic equations of the basic partial differential equation, "(f,θ) particles" move along the rays (characteristics) from ray point to ray point, and grow in a certain way. The arrays of these spectral words, and other arrays (e.g., various moments of the spectra), are initialized in WAVESET and stored in "tape" (usually disk) files. Tables 1A-B show block diagrams of WAVESET.

B. PROPAGR

The basic function of PROPAGR is to modify the spectral density of and on appropriate time steps to propagate the spectral words. (The "energy" carried by these particles (words) has units of $(\text{length})^2$ (time)/radian.) PROPAGR consists mostly of a set of nested loops. The outermost loop is a time step loop. One pass through this loop calculates everything that takes place in the simulated wave field during one time step or cycle.

Within the time step loop are calculations of certain quantities that are constant for that time step, and a loop over all frequencies. At the end of each time step, when the directional spectrum has been evaluated, it is possible to calculate spectral moments, such as f_m* and E_{max}.

*Frequency of spectral peak; arbitrarily initialized to 0.25 Hz.

TABLE 1A

FUNCTIONAL BLOCK DIAGRAM, WAVESET

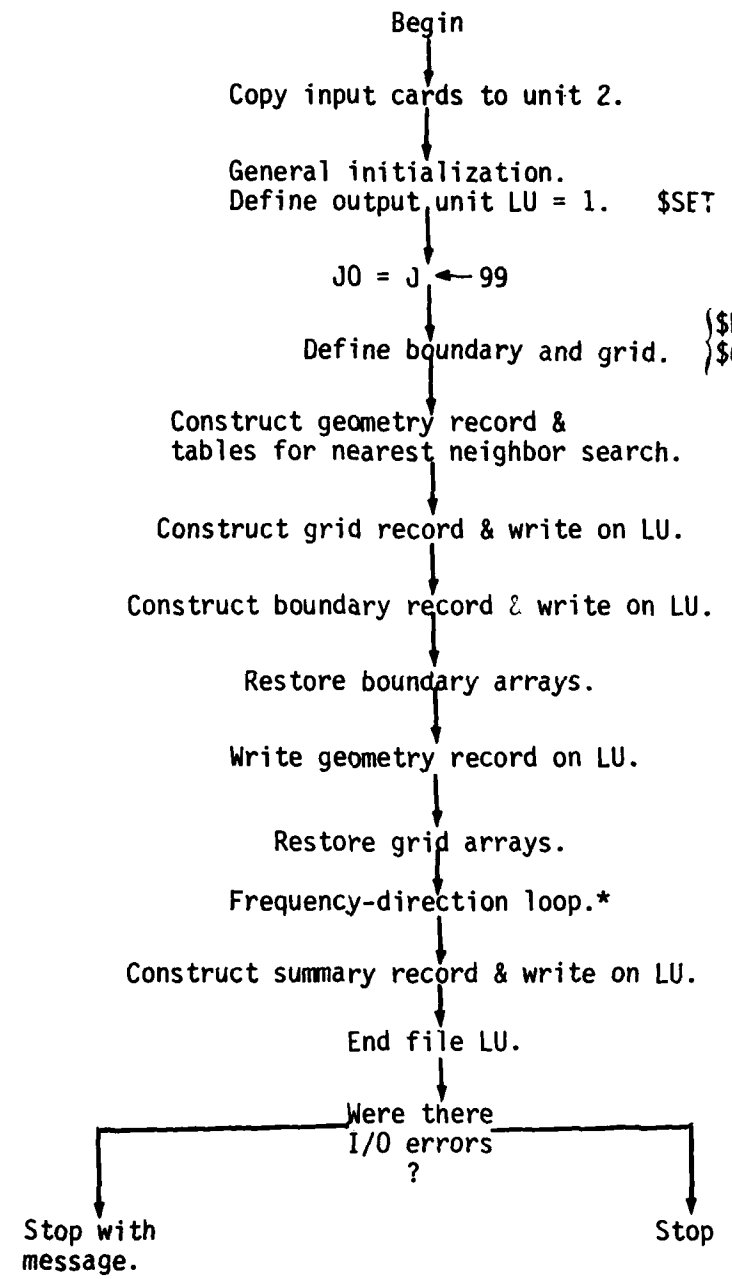

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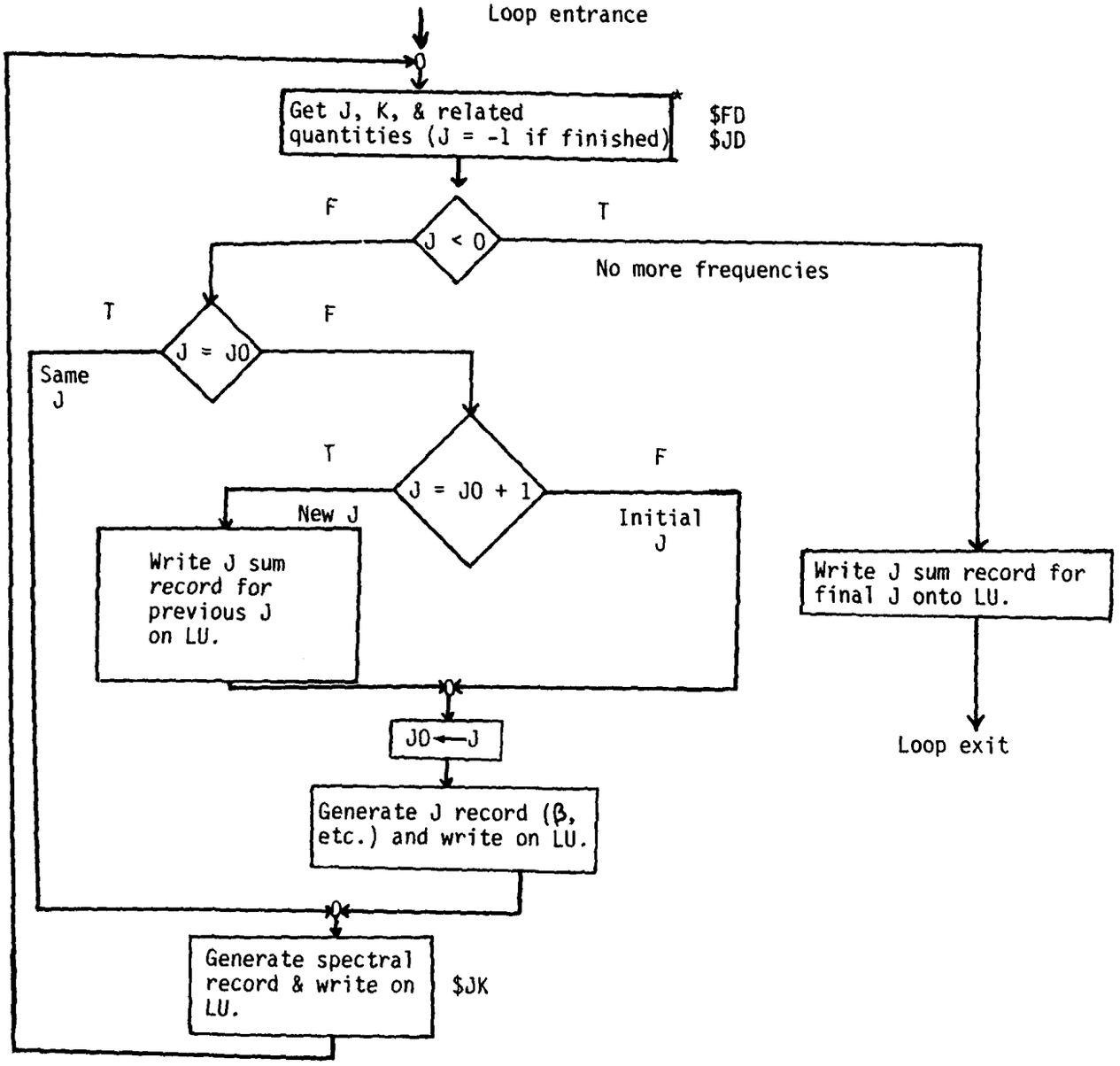
TABLE 1B

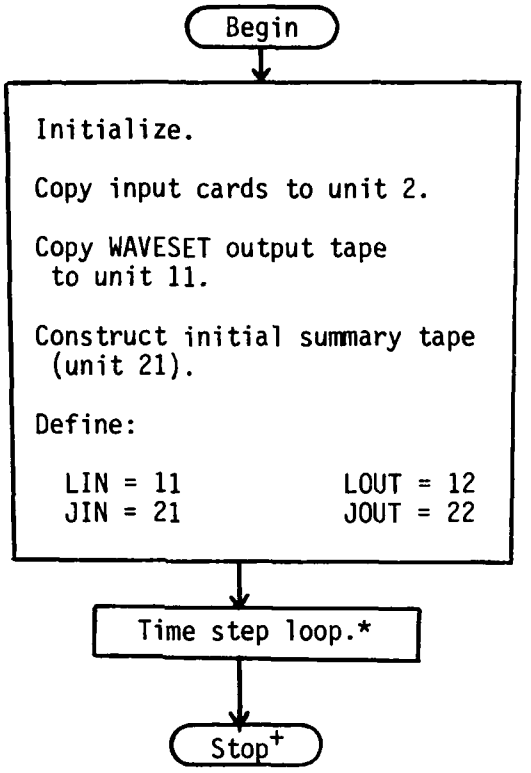
FREQUENCY-DIRECTION LOOP, WAVESET



*J = frequency index, K = direction index.

TABLE 2A

FUNCTIONAL BLOCK DIAGRAM, PROPAGR

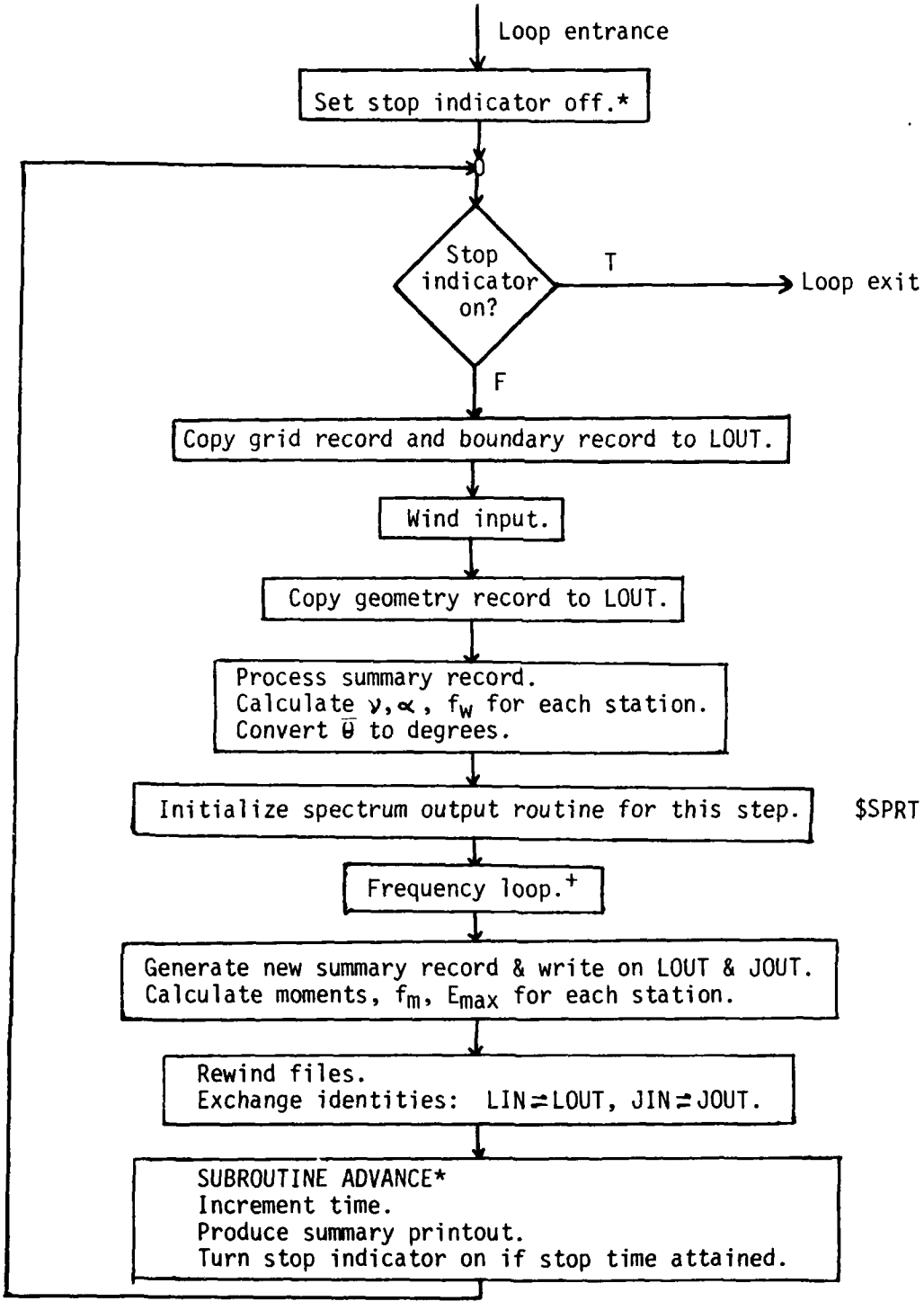


*Next page.

+Stop test & stop contained in SUBROUTINE ADVANCE (in time step loop).

TABLE 2B

TIME STEP LOOP, PROPAGR



*Stop test & stop contained in SUBROUTINE ADVANCE.

+Next page.

TABLE 2C

FREQUENCY LOOP, PROPAGR

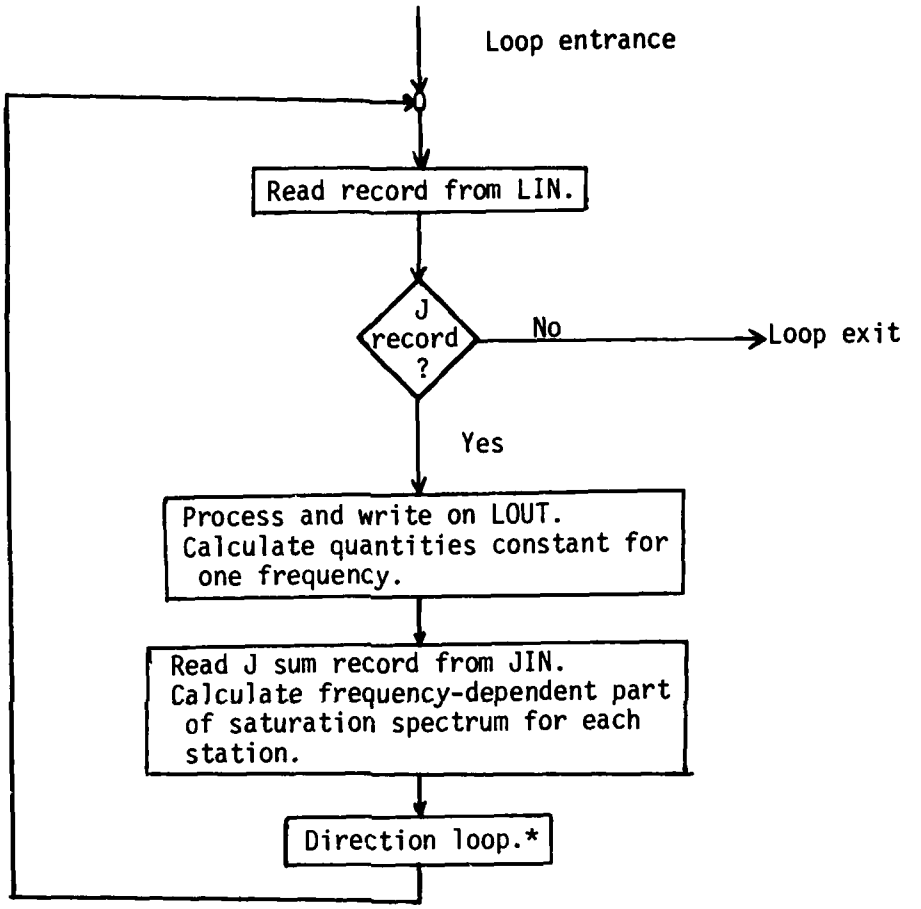


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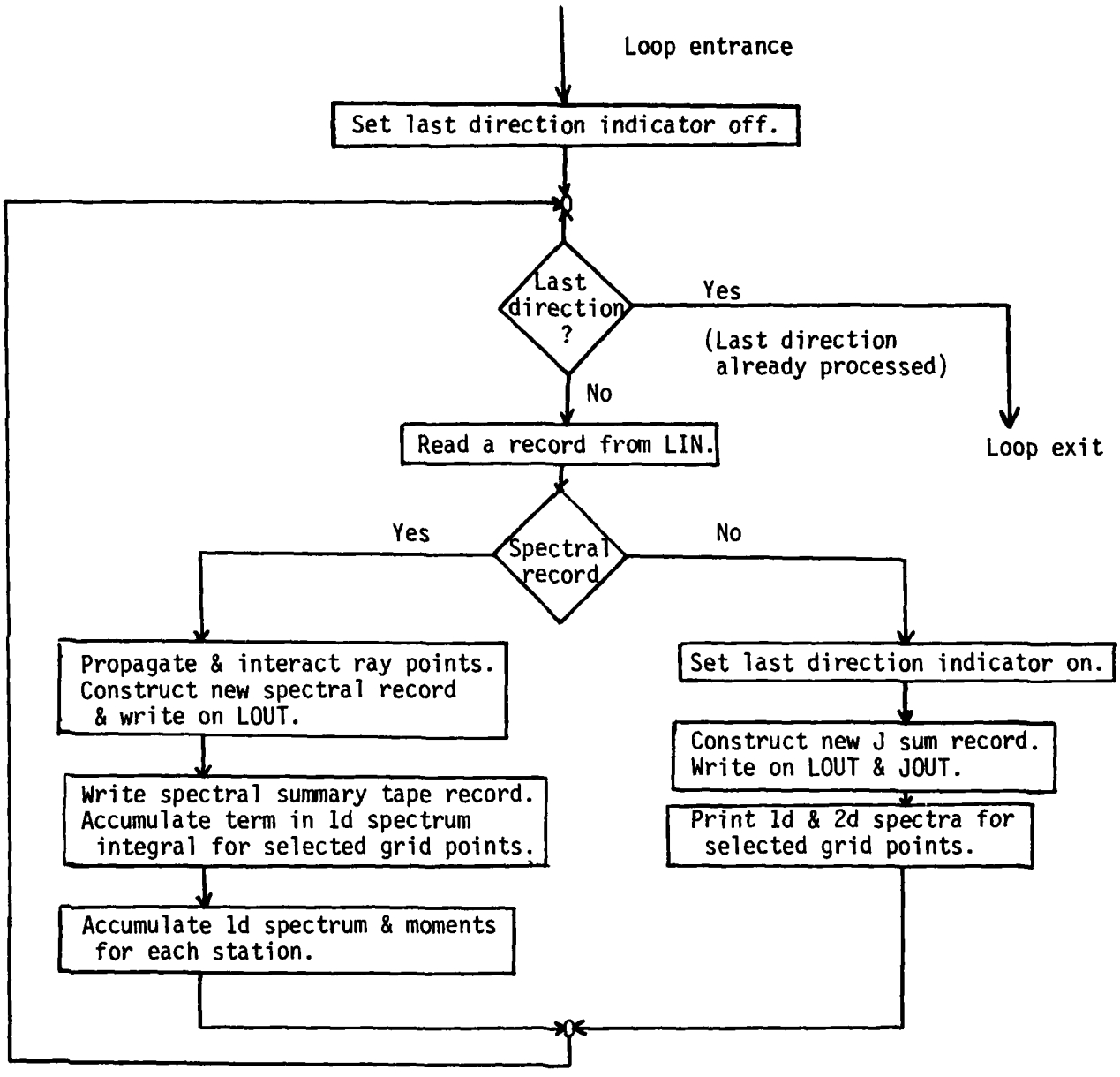
TABLE 2D

DIRECTION LOOP, PROPAGR



Within the frequency loop there are calculations of quantities constant for a given frequency and there is a loop over directions. The calculations that directly involve the spectral words take place within the direction loop. Propagation and interaction take place, and the summations for the 1d spectram and the moments are accumulated.

Two types of files (external storage) are used to pass the complete state of the system from one cycle to the next. The cycle tape contains information on the grid, boundaries, details of the geometry, quantities constant for each frequency, spectral words and related information, integrals of energy over direction, and integrals over both direction and frequency. The spectral words and integrals are also written on a summary tape. One pair of these files serves as input to a cycle; another pair is output. In addition, for output purposes, a spectral summary tape is created. This file contains the directional spectrum at each grid point (found by nearest neighbor interpolation). The subroutine that writes this file also can print the 1d and 2d spectra at selected grid points. Tables 2A-D show block diagrams of PROPAGR.

III. CALCULATION OF SOURCE FUNCTIONS FOR SPECTRAL DENSITY

A. MOMENTS

The following quantities are calculated at each grid point (using nearest neighbor interpolation on ray point values where needed).

1. The variance (energy) EAV, which includes an f^{-5} tail, is defined by

$$ESUM = \sum_j \sum_k F(f,\theta)\, \Delta f_j\, 2\pi\, \Delta\theta_k$$

$$SE = \sum_{i=1}^{100} \frac{.0081\, g^2\, (2-f_{max})/100}{(2\pi)^4\, [f_{max} + i\,(2-f_{max})/100]^5}$$

$$EAV = ESUM + SE$$

Here f_{max} is the highest discrete frequency used in the model, not the frequency of the spectral peak, and g is the acceleration of gravity.

2. The mean frequency FQAV accounting for an f^{-5} tail is found from

$$FQSUM = \sum_J \sum_K F(f,\theta)\, f_J\, \Delta f_J\, 2\pi\, \Delta\theta_K$$

$$SFO = \sum_{i=1}^{100} \frac{.0081\, g^2\, (2 - f_{max})/100}{(2\pi)^4 \left[f_{max} + i\,(2 - f_{max})/100\right]^4}$$

FQAV = (FQSUM + SFO)/EAV

3. The mean wave direction THAV is

$$THSUMS = \sum_J \sum_K F(f,\theta) \sin\theta_K\, \Delta f_J\, 2\pi\, \Delta\theta_K$$

$$THSUMC = \sum_J \sum_K F(f,\theta) \cos\theta_K\, \Delta f_J\, 2\pi\, \Delta\theta_K$$

THAV = $\tan^{-1}$ (THSUMS/THSUMC)

4. The rms directional spread S is

$$THRSUM = \sum_J \sum_K F(f,\theta)\, (\theta_K - \bar{\theta})^2\, \Delta f_J\, 2\pi\, \Delta\theta_K$$

S = THRMS = $(THRSUM/EAV)^{1/2}$

and $\bar{\theta}$ = THAV.

B. OTHER SPECTRAL PARAMETERS

Additional parameters needed to evaluate the source functions are found as follows.

1. The peak frequency of the 1-D spectrum FM and the maximum E_{max} are found by fitting a quadratic to the discrete peak and evaluating the quadratic at its maximum. (Assuming the discrete peak occurs at subscript 2 (arbitrary choice) the formulas are:

$$a_0 = [F_1(f_1f_3^2 - f_3f_2^2) + F_2(f_3f_1^2 - f_1f_3^2) + F_3(f_1f_2^2 - f_2f_1^2)]/D$$

$$a_1 = [F_2f_3^2 - F_3f_2^2) + (F_3f_1^2 - F_1f_3^2) + (F_1f_2^2 - F_2f_1^2)]/D$$

$$a_2 = [(f_2F_3 - f_3F_2) + (f_3F_1 - f_1F_3) + (f_1F_2 - f_2F_1)]/D$$

$$D = \det \begin{vmatrix} 1 & f_1 & f_1^2 \\ 1 & f_2 & f_2^2 \\ 1 & f_3 & f_3^2 \end{vmatrix}$$

The derived location and value of the maximum then are

$$F_M = -a_1/(2a_2)$$

$$EMAX = a_0 - a_1^2/(4a_2)$$

2. The saturation range (or energy level) parameter α for use in the limiting form of the spectrum, the nondimensional peak frequency ν, and the wind frequency f_u are defined as:

$$\nu = ANU = U\ FM/g$$

$$\alpha = ALP = 0.032\ \nu^{2/3},\ .0081 \leq \alpha \leq .02$$

$$f_u: \begin{cases} FW = 0.13\ g/U, & U \neq 0 \\ FW = 1.0, & U = 0 \end{cases}$$

3. The peakedness GAMA of the 1-d spectrum compared to a Pierson-Muskowitz spectrum EPM is

$$EPM = 176.5\ ALP/(FM)^5$$

γ = GAMA = EMAX/EPM, $1.0 \leq GAMA \leq 4.0$

4. The scaling term to convert refrence values of the nonlinear transfer S_{nl} to values appropriate for an evolving model spectrum is

$$D = \frac{(EAV)^3(FQAV)^8(10^4)/(1.26(10^{-9})g^4)}{[1 + 0.235(GAMA-1)]}$$

C. ATMOSPHERIC INPUT

The form of S_{in} used in the present model yields an exponential growth mechanism. The linear growth mechanism, operative in the old model, is no longer used. The source function has the same form as described by Barnett (1968), but has been reduced by a factor of four; the nonlinear transfer (Sec III.D) makes up the difference in the present model. The source function is simply:

$$S_{in} = 0.25\beta Y$$

where Y is the spectral density of a given (f,θ) particle and the growth coefficient β is precomputed in WAVESET for 5-knot intervals of wind speed. Note also that β is nonnegative and that S_{in} is evaluated with respect to the local wind direction in the program.

D. NONLINEAR TRANSFER

The nonlinear transfer is represented by a set of empirical orthogonal functions (eof's) that decompose a body of exact calculations of the transfer for a family of single-peaked spectra with different peakedness γ and angular spread s. The theoretical calculations were made by Hasselmann and Hasselmann (1981). The eof's were constructd by T. Barnett at Scripps Institution of Oceanography. The

formula used to evaluate S_{nl} at model grid points is:

$$S_{nl}(f,\theta) = D\left[ABAR(\gamma,s) + ASD(\gamma,s)\left\{\bar{S}_{nl}(\hat{f},\theta_{II}) + \sum_{1}^{5} A_n(\gamma,s)\,B_n(\hat{f},\theta_{II})\right\}\right]$$

where $f = f/FM$ and $\theta_{II} = |\theta - \bar{\theta}|$. The following parameters ranges are used:

$$0^\circ \le \theta_{II} \le 60^\circ, \quad \Delta\theta_{II} = 15^\circ$$

$$1 \le \gamma \le 4, \quad \Delta\gamma = 0.1$$

$$0.45 \le s \le 0.70, \quad \Delta s = 0.05$$

$$0.66 \le \hat{f} \le 1.95, \quad \Delta\hat{f} = 0.01$$

The mean ABAR and standard deviation ASD were extracted from the theoretical transfer before finding eof's so that all parts of the (γ,s) range would have roughly equal weighting. The B_n can be thought of as the eof's and the A_n as amplitudes of these eof's.

E. LIMITING SPECTRUM

We employ the well-known Pierson-Moskowitz spectrum evaluated at the local wind frequency, but with a variable saturation range parameter, as our spectral limiter. The limiting value Y_{max} for given f,θ is

$$YMAX = \frac{\alpha g^2}{2^4 \pi^5 f^5} \exp\left[-5/4\,(f_u/f)^4\right] \cos^2(\theta - \theta_u)$$

The logic used to apply the limiter is described in Sec. IV.C.

IV. SOLUTION OF THE GROWTH AND PROPAGATION EQUATIONS

A. OVERVIEW OF SUBROUTINE INTRACT

We neglect refraction and the curvature of the earth, and assume that the evolution of spectral density F is governed by a radiative transfer equation with the general form:

$$\frac{d}{dt} F(x,y,f,\theta,t) = \left(\frac{\partial}{\partial t} + c_g \cdot \nabla\right) F = S$$

where S is the net source function. INTRACT sets up the source terms (mostly calculated elsewhere) that apply for the conditions at each grid point (recall that the grid is constant for all directions and frequencies). Then the ordinary differential equation given above is integrated for each ray point (sampled position along one of a family of parallel characteristic "curves" for the given direction and frequency), and the propagation logic is applied.

In one time step of duration Δt, energy of a given frequency can move a distance $C_g \Delta t$, where C_g is the group velocity of waves of that frequency. In some cases $C_g \Delta t$ may be small compared to other distances of interest. The program has the capability of holding up propagation for MXSTEP (a program variable) steps, while still allowing energy growth. Then consecutive ray points are (MXSTEP) $C_g \Delta t$ apart; MXSTEP may be different for each frequency.

The energy content of ray points on the incoming boundary is fixed at a very small value ($<10^{-200}$). When MXSTEP>1, this condition holds until the energy packet steps to the next ray point. Then and only then does the growth equation apply. Points that reach the outgoing boundary are absorbed perfectly; there is no reflection or other effect.

B. EQUATIONS IMPLEMENTED

Propagation and growth are logically separated. The propagation condition is

$$x - C_g t = 0$$

where x stands for the position along one of the characteristic rays. As described above, propagation takes place every MXSTEP time steps (MXSTEP is an integer ≥ 1), so the propagation condition becomes

$$\Delta x = C_g \, (\text{MXSTEP} \cdot \Delta t)$$

where x is the distance moved. As implemented in the program, the array that holds energy values at positions along rays has consecutive elements that are assumed to be ΔX apart along a given ray; the first point on each ray is always assumed to be on the incoming boundary. On propagation steps an (f,θ) particle or bundle of energy is simply moved to the next-indexed array element. (Implementation detail: An entire family of rays is treated as one array. When an energy packet moves from the last position on one ray to the next array location, which represents the incoming boundary point on the next ray, the no-reflection boundary condition is automatically applied.)

As described in Section III, we assume that the net source function S is dominated by the two physical processes:

$$S = S_{nl} + S_{in}$$

where S_{nl} is synthesized from empirical orthogonal functions, and

$$S_{in} = (\beta/4)Y$$

where Y is shorthand for the directional spectrum at the particular frequency, direction, location, and time under consideration. A hybrid integration scheme is used: first-order Euler for S_{nl} and effectively an implicit trapezoidal integration for S_{wind}. The composite integraton equation for advancing to time step n+1 is

$$Y^{n+1} = Y^n + S_{nl}\,\Delta t + \left[\frac{1 + \frac{1}{2}(\beta/4)\,\Delta t}{1 - \frac{1}{2}(\beta/4)\,\Delta t} - 1\right] Y^n$$

$$= Y^n + S_{nl}\,\Delta t + \frac{1}{2}\left(Y^n + Y^{n+1}\right)\frac{\beta}{4}\,\Delta t$$

If this is a propagation step then Y^n and Y^{n+1} are evaluated at different locations. The quantities β and S_{nl} are evaluated at the same location as Y^n ("growth before propagation"). The limiting form of the spectrum is then invoked as necessary according to the logic discussed in the following section.

C. LOGIC FOR APPLYING SPECTRAL LIMITER

The maximum spectral density at any ray point at any time is governed by the limiting form of the spectrum. Numerous logic statements are used to decide whether the maximum density should be imposed. These statements can be divided for purposes of explanation into 4 catagories: subgrid saturation region, swell region, integrator, and saturation region.

1. In the subgrid region all other calculations are by-passed and an (f,θ) particle is immediately assigned its maximum density. Associated with each frequency is a wind speed USAT above which wave growth is so rapid that it cannot be resolved in the model. Measurements of net growth by Barnett and Wilkenson (1967) are combined with the notion that the fractional change in density cannot be greater than DSAT in one time step, viz.

$$\Delta F/_F = \beta(U,f)_{net}\,\Delta t \leq DSAT$$

The value DSAT=1.5 was used in the earlier version of the model. The logic is simply

If U>USAT(f), then $Y=Y_{max}$

2. Swell Region

Wave growth below the wind frequency f_u is prevented if the spectrum is already greater than or equal to the limiter.

If $f<f_u(X_i)$ and $S_{nl}(x_i) > 0$ and $Y>Y_{max}(x_i)$, then set $S_{nl}(x_i)=0$; else skip.

3. Integrator

The incremental change DF to the spectrum during a time step is forced to be nonnegative (severely notched spectra were obtained without this provision.)

If $f \geq f_u$, then limit $DF \geq 0$

$y^{n+1} = y^n + DF$

4. Saturation Region

Application of the limiting form for spectral density depends on f_m, f_u, $\theta - \theta_u$, and in some cases the density at the previous time step.

a. If $f < f_u(x_{i+1})$ then do nothing

b. Else (active generation, $f \geq f_u(x_{i+1})$

(1) If $|\theta - \theta_u| \leq 90°$ (forward half-plane) then

If $Y \leq Y_{max}(x_{i+1})$ then do nothing

Else ($Y > Y_{max}(x_{i+1})$

If $f \leq f_m(x_{i+1})$ then

If $Y^n > Y_{max}(x_{i+1})$ then set $Y^{n+1} = Y^n$

Else ($Y^n \leq Y_{max}(x_{i+1})$) set $Y^{n+1} = Y_{max}(x_{i+1})$

Else ($f > f_m(x_{i+1})$) set $Y^{n+1} = Y_{max}(x_{i+1})$

(Zero (infinite) decay time for components above (below) local peak)

(2) Else $|\theta - \theta_u| > 90°$ (back half-plane)

If $f > f_m(x_{i+1})$ then set $Y^{n+1} = 0$ (saturation).

Else ($f \leq f_m(x_{i+1})$) do nothing

(3) Eliminate negative values - Limit $Y \geq 10^{-62}$.

D. SOURCE (Y) AND DESTINATION (X) CONCEPT FOR PROPAGATION

The program uses an array of "spectral words" each of which contains the energy density (directional spectrum) at a certain location (ray point), for the

frequency and direction being treated. In one time step the value of a spectral word generally changes, and if it is a propagation step the location also changes. The program uses two temporary variables, X and Y. Roughly speaking, Y is a "source" and X is a "destination". As each point in the array is processed Y starts off with the value for location x_i at the beginning of the time step. Application of the net source function to the old spectrum value creates X. X is stored into the same array location for non-propagation steps, or into the next locations for propagation steps. Using previous notation, $Y = Y^n$ and $X = Y^{n+1}$. Y is associated with location x_i, X is associated with x_{i+1} or x_i, depending on whether propagation does or does not take place, respectively.

E. TEMPORARY CHANGES

The subgrid saturation logic was not used for the wave model intercomparison (Hasselmann et al., 1982). We made two temporary changes to try to handle problems that arose at relatively high frequencies. First, the saturation condition was applied to certain (f,θ) particles which otherwise would not receive any spectral density (having encountered no ray point 'upwind' where DF > 0). The logic was

if propagation step and $f \geq f_u(x_i)$ and $f > f_m(x_i)$ and $Y < 10^{-20}$

then $Y = Y_{max}$

Second, an exponential filter was added to combat a sawtooth effect in the spectrum at short fetches. The recursive filtering scheme was

$$\tilde{Y}^{n+1} = \tilde{Y}^n + DF + e^{-1/N}\,(X-Y)$$

where the tildes indicate smoothed values and N = MXSTEP/8 (where MXSTEP is the number of time steps between propagation steps) was used.

We strongly recommend that these changes be removed from the model, and for practical calculations replaced with a subgrid mechanism such as described in

IV.C.1. These temporary changes helped very little and actually caused minor problems.

V. USER INSTRUCTIONS

A. WAVESET data cards

[NOTE: Variables read in on NAMELIST data cards and their default values (if any) are defined in comments at the beginning of WAVESET (main program). The comments show the NAMELIST names preceded by an asterisk. In the current version the asterisk is replaced by a $ sign in column 2 (e.g. _$SET, __$BOND, etc.).]

The first card has *RUN in cols. 1-4. Text (title information) may appear in cols. 7-22.

The next data card is the _$SET card. Important parameters are listed below:

XOS, YOS

SZERO

EZERO

FQZERO

SCALE (= .53996 for distances in km)

DTIME

NSTEP (= 0 normally)

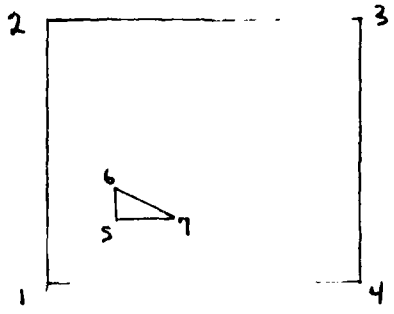
INITDT*

Internal grid points and boundary points are the external values (from data cards) with XOS & YOS subtracted:

$$(X,Y)_{int} = (X,Y)_{ext} - (XOS,YOS)$$

*Initial date and time may be specified by giving ITIME = time in seconds since midnight, Jan. 1, 1900.

The boundary is specified by the _$BOND card. For a single basin it is sufficient to specify NBOND > 2 and the XBOND & YBOND lists. For a more complicated situation (e.g. islands) a little more information is needed. Example: Suppose the basin is 10 x 10 with lower left corner at (0,0), containing a right triangular island extending 2 units in X and 1 unit in Y, with the right angle at (2,4). Then the data card should be




```
$NBOND   NBOND = 7,
         XBOND = 0, 0, 10, 10, 2, 2, 4,
         YBOND = 0, 10, 10, 0, 4, 5, 4,
         NBSTART (2) = 5   $END
```

NBSTART (1) defaults to 1 and need not be specified. There are limits of 200 boundary points and 9 islands.

Grid points are specified by _$GRID cards. There are three methods, which may be combined:

(1) Specify DX, DY, XS, YS. Then points will be generated at (XS + mDX, YS + nDY), m = 0, $\pm$1, $\pm$2, ---; n = 0, $\pm$1, $\pm$2, ---. All points that fall within the boundary will be retained. The program counts the points that are generated and retained.

(2) Give LATTICE $\neq$ 0, XLIST and YLIST arrays, and NX and NY. The program generates grid points at all intersections (XLIST(n), YLIST(m)), n = 1,2,---,NX, m = 1,2,---,NY, and counts the points.

(3) Explicitly list the grid points (elements of XGRID and YGRID arrays). To use this method properly it is necessary to know NGRID = number of grid points that have already been specified. The explicit lists begin with XGRID(NGRID + 1) and YGRID(NGRID + 1). It is also necessary to redefine NGRID to account for the number of points in the lists.

Grid point input is terminated when the last _$GRID card leaves LATTICE and at least one of DX,DY unset. In some cases an extra _$GRID card is required to do this. There is a limit of 500 grid points.

A list of up to 20 frequencies may be read in using a _$FD data card. The frequencies must be ordered monotonically increasing. The remaining cards are keyed to the frequency list. [A mistake in the original program that prevented the 20th frequency from being read was corrected.]

The remaining NAMELIST cards (_$JD and _$JK) specify the families of rays. The following must be specified: directions, lateral spacing between individual rays, and spacing between points on the rays (where energy is localized during propagation). Families of parallel rays are generated in directions that are derived from information on _$JD card(s). The directions are usually specified for the first frequency and remain specified for subsequent frequencies, although they can be redefined. The first nine (9) columns of the card have a mandatory format: _$JD_Q=jj, where jj is the index of the specified frequency (e.g., 0) for the first frequency in the _$FD list). Directions are specified by a list KDIR. The KDIR values are <u>not</u> the ray directions. Rather, they are directions to cut the unit circle into "pie slices". The ray directions are along lines that bisect the vertex angles of the pie slices. This guarantees that the influence of a given direction

(in integrals, e.g.) is symmetric about that direction. Up to 36 KDIR values may be specified.

The value MXSTEP is also given on _$JD cards; it determines the spacing between points on a ray. A natural length unit for the propagation problem is (group velocity) x (time step). Ray points may be placed at any integral multiple of this distance (starting on the incoming boundary); MXSTEP is the multiplier. The same MXSTEP value remains in effect until it is redefined.

So, a card of the form

```
_$JD_Q=0100, KDIR = 0, 30, 60, 90, 120, 330,
  MXSTEP = 2 $END
```

specifies the following situation: beginning with the first frequency, families of parallel rays are generated in the directions 15°, 45°, 75°, 105°, 225°, 345°. The spacing between successive points on one ray is twice the basic natural unit of length. These parameters remain in effect until they are redefined.

As diagrammed in II.A, processing effectively involves nested loops: for each frequency in turn, the program cycles through each direction. For each direction (for each frequency) the spacing between parallel rays may be specified, using _$JK cards. The first eleven (11) columns of these cards must have the format _$JK_Q=jjkk, where jj gives the frequency index, as for _$JD cards, and kk gives the direction index. There are three ways to specify ray spacing.

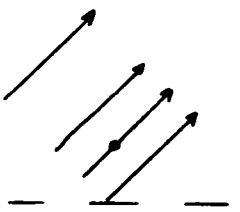
(1) The RAYSPAC parameter explicitly gives the distance between rays. In general, the number of rays will depend on their direction.

(2) The RAY list (up to 100 values) provides a method of obtaining unequally spaced rays, among other things. If we define a right-hand coordinate system whose origin coincides with the origin of grid and boundary coordinates, and whose

positive x-axis extends in the ray direction, then the RAY list gives the y-coordinates of the rays. For example, in the 45° direction the list

RAY = -1, 0, 1, 3

gives the rays shown at right.



(3) The NRD parameter defines ray spacing as a fraction of the transverse width of the basin. If we construct a pair of lines in the ray direction that are tangent to the basin at the maximum possible distance on either side of the origin; then the distance between these lines is the "transverse width". A value of NRD = 30 creates a uniform ray spacing 1/30 of this value. Then the distance between rays will depend on direction, but the number of rays will be NRD for all directions. For example, a card of the form

_$JK_ Q=0101, RAYSPAC = 25 $END

begins with the first frequency and the first direction, and specifies rays 25 external length units (SCALE x nautical miles) apart. This specification remains in effect for all frequencies and directions until it is redefined.

It is permissible to intermix _$JD and _$JK cards as needed. For example, MXSTEP may be redefined at higher frequencies to prevent the ray point spacing from becoming significantly less than the grid point spacing as group velocity decreases.

WAVESET data card input is ended by a card of the form

_$STOP___.

B. PROPAGR data cards

The first data card has _$RUN in columns 1-4, with text in columns 8-25. The text is used as a page title every tenth time step.

The next card is a _$DBTA NAMELIST. Only two of the variables are significant in the present version:

STEP = starting time step (= 0 normally to agree with WAVESET)

STOP = stop data and time in form mm,dd,yy,hh,mm,ss

Note: One step is performed with step = 0, i.e. at the initial time, and the stopping condition is such that the time of the last step performed must be greater than the stop date-time. So the number of processing steps is

[((stop date-time) - (start date-time))/(time step)] + 2

The next data card has the form

_$GO text.

The preceeding card, and the complete $DBTA NAMELIST, are printed before processing begins.

The subroutine that produces the spectral summary tape, and associated printout, is controlled by a _$SPRT NAMELIST card. The variables are:

NSP = Number of stations (grid points) to print ($\leq$ 20)

LOC = List of stations to print

NPR = Time step interval for printing

NSV = Time step interval for saving data on spectral summary tape

For the purposes of this output, the first (dummy) time step is treated as step 1. Also, NPR must be an integral multiple of NSV. Thus, if DTIME = 1200 (1200 seconds = 20 minutes; value set in WAVESET), NSV = 3, and NPR = 24, then information is written on the spectral summary tape every hour (after 3, 6, 9, --- time steps), and printout is produced every 8 hours.

The final data card is

_*STOP_____,

exactly the same as for WAVESET.

C. GRID/RAY POINT RELATIONSHIP

For each frequency-direction combination there are effectively two grids - the "grid" and the "rays". The former is used to (resolve and) specify the source term fields, and to provide a convenient ouput mechanism; the latter forms the spatial mesh on which the discrete approximation to the radiative transfer equation is solved, so it must resolve the wave field. The grid is a fixed lattice of points, whereas a different set of ray points is used for each frequency-direction combination.

The program limits the number of grid points to 500. Approximately 2000 ray points in each set are allowed. A very fine ray point spacing might improve the accuracy of the integration, except that the source terms to be used at a ray point are taken to be those calculated at the nearest grid point. Consequently, there is no point in making the ray point spacing much smaller than the grid point spacing. We believe that a good rule of thumb for regular grids is to make the ray point spacing approximately equal to the nearest neighbor spacing of the grid. For example, for a square grid this is about 2/3 of the grid interval.

Another consideration applies an upper limit to the spacing of points along rays. The nonlinear interaction source term, calculated at grid points, involves integrals over the spectral density. The latter is calculated at ray points. So the integrals are calculated by obtaining the directional spectrum, for each direction and frequency involved, from the ray point nearest to the grid point "at" which the calculation is performed. This mutual relationship -- energy values at ray points are affected by source terms at the nearest grid point; the source terms involve spectral values at nearby ray points -- is referred to as the "region of influence" concept.

Now the first point on each ray is on the incoming boundary and is constrained to have a very small value. Consequently, it is important to prevent the grid points closest to the boundaries from "looking" at these boundary ray points in calculating spectral moments, because the moments would be underestimated and the effect would "feed back" to other ray points via the interaction.

The current solution to this problem is to arrange the grid-ray layout so that grid points close to boundaries "look" at the second (or later) points along rays. WAVESET could be modified to that the grid point-ray point linkage logic would prohibit a grid point from being linked to a boundary ray point. The modification is not trivial. Inclusion of subgrid scale wave growth also would help to reduce this problem.

VI. OUTPUT FORMATS

A. CYCLE AND SUMMARY TAPES

In each time step, 10^5-10^6 directional spectrum values are updated. The source term calculation and interaction logic also involves thousands of other values. This extremely large number of variables is handled by the use of external storage. The complete state of the system is kept in a file, which is designated the cycle tape. Spectral moments are also kept on a separate summary tape. There are two cycle tapes, A and B, and two summary tapes, C and D. In one cycle step PROPAGR advances the solution one time step by processing A and C to produce B and D, containing the updated values. In the next time step the roles are reversed. The initial state is set up by WAVESET (cycle tape only; the initial summary tape is created by PROPAGR's initialization routine). The cycle and summary tapes at the end of processing serve as the primary means of output for the final state.

The cycle tape format is shown in Table 3. There is one group of JREC, JKREC, JSREC records for each frequency; all of the groups precede the SREC record. The JREC, JSREC, and SREC records also appear on the summary tape. A detailed description of ecah type of record on the cycle tape is given in Table 4.

B. SPECTRAL SUMMARY TAPE

The spectral summary tape contains the directional spectrum and a few other pieces of information. Unlike the cycle and summary tapes, the spectral summary is cumulative -- information is written to it every NSV time steps (V.B). At each time step for which information is written to tape, a 5-word ID record and several spectral records -- one for each direction for each frequency -- are written. For convenience in interpretation, spectra are evaluated at (all) grid points, using nearest-neighbor interpolation. The structure of the individual records is described in Table 5.

VII. SUMMARY

The present model, a modified version of the original model by Barnett et al. (1969), received its first workout in the wave model intercomparison (Hasselmann et al., 1982). The model imitated the JONSWAP laws, although it is not based on them directly. The model produced good results for many ideal cases of wave generation from a simple fetch-limited situation to the complex situation of a rapidly moving hurricane. We found a lot of chatter in the spectral values (and the various moments) at fetches less than about two grid lengths because the gradients in the wave field were not resolved. A short test with a 5-fold increase in spatial resolution cured the problem but was, of course, impractical. We also caused some isolated, undesirable peaks to appear in complex situations through the temporary changes discussed in IV. More than likely both of these problems would be cured by using some mechanism for subgrid wave growth as suggested in IV.C.1. (All in all the view we took for the intercomparison was too pristine.)

TABLE 3

CYCLE TAPE FORMAT

RECORD	REMARKS	LENGTH
GRIDREC	Misc. data & grid point coordinates	2 x NGRID + 9
BONDREC	Boundary description	2 X NBOND + 13
GREC	Geometry description used to set up linkages	LGREC $\leq$ 2000
JREC	J (frequency) coefficients	LJREC (= 812)
JKREC	Spectral densities, one record for each direction	$\leq$ 2049
JSREC	Sums over directions for this frequency	NGRID + 2
SREC	Sums over frequency and direction	3 x NGRID + 12

TABLE 4

CYCLE TAPE RECORDS*

GRIDREC

0	$ID=200_8$	
1	NGRID	
2	SCALE	
3	CDIST	
4	DTIME	(sec)
5	ITIME	(sec)
6	XOS	
7	YOS	
8	XGRID (NGRID)	INTERNAL COORDINATES
NG+8	YGRID (NGRID)	
2NG+8	ID	

BONDREC

0	$ID=201_8$	
1	NBOND	
2	NSTART (10)	
12	XBOND (NBOND)	INTERNAL COORDINATES
NBOND+12	YBOND (NBOND)	
2NBOND+12	ID	

GREC

0 $ID=400_8$ for 1st grid point

NN	MORE+	BYTE	BYTE
15	15	15	15

1 GREC (LGREC)

for NGRID

NN	MORE+	BYTE	BYTE

*Note that word counts in records start with 0, not 1.

+Pointer to continuation word.

TABLE 4 (Cont.)

	GREC (MORE)	BYTE | BYTE | BYTE | BYTE
LGREC+1	ID	
JREC		
0	$ID=600_8+J$	
1	$WINDMAX_J$	IWMAX, RSTA, EIGHT(8) wind above which saturation occurs, saturation value, extra stuff
11	ALPHA (40, 10) ←	interaction coefficients
411	BETA (40, 10) ←	for this scheme.
811	ID	
JKREC		
0	ID = | 0 (15) | NSTEP (15) | J (15) | K (15) |	One per freq., per direction i.e., Lots!
1	NP	No. of points
2	NNB	Number of Neighbor Words
3	MS	Step counter for this J, K modulo MXSTEP
4	MXSTEP	
5	KDIR	0 to 360 integer
6	DDIR	ΔKDIR/360 (sum to 1.00)
7	DFREQ	
8	FREQ	
9	X }	unused
10	X }	

TABLE 4 (Cont.)

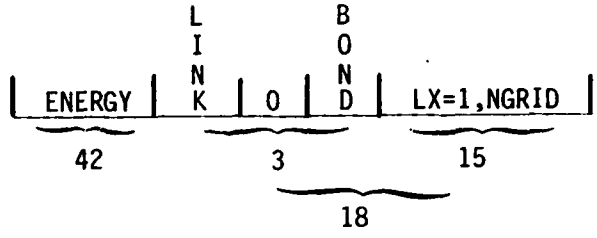
11	SPECT(NP)	
		LX Index of nearest grid point
		LINK=1 this ray pt also nearest to that grid point, else LINK=0
		BOND=1 this is a boundary point (incoming)
NP + 11	NBT(NNB)	Neighbor table. For each grid point LX that is not the nearest neighbor of any ray point, i.e. a grid pt w/no links, this gives the ray point IX that is nearest.
		NBT | IX (30) | LX (30) |
		IX closest to LX where LX not closest to IX.
NP+NNB+11	ID	
JSREC		
0	ID =	| 0 | NSTEP | J | 100 |
1	SEJ(NGRID)	Integrals of energy over direction but for this freq.
NGRID+1	ID	
SREC		
0	JD = NSTEP*2^{30}+100B	
1		
2	NGRID	
3	JMAX	
4	EZERO	
5	FQZERO	

TABLE 4 (Cont.)

6	THZERO
7	ITIME
8	X }
9	X } not used
10	X }
11	SE (NGRID)
NG+11	SFQ (NGRID)
2*NG+11	STH (NGRID)
3*NG+11	ID

[NG = NGRID]

TABLE 5

SPECTRAL SUMMARY TAPE DESCRIPTION

ID RECORD

1	ID	7777777777777777STEP (octal)
2	LEN	total length (=5)
3	ITIME	time in seconds since 1/1/00
4	JMAX	number of frequencies
5	NGRID	number of grid points

DIRECTIONAL SPECTRUM RECORD

1	ID	1000_8 x JFREQ + KDIREC
2	LEN	total length = 4 + [(NGRID + 1)/2]
3	DF, F	Δf, f (30 bits each, packed)
4	DTH, K	$2\pi\Delta\theta$, θ* (30 bits each, packed)
5	SP1, SP2	Spectrum at first two grid points
⋮		(30 bits each, packed)
LEN ...	SPN	spectrum at last (one or two) grid point(s)

*Angle in degrees.

An open question is: how should the model respond to a rapidly changing wind direction? The present version probably produces too large a drop in the variance of the spectrum when there is a change in the wind field, although the rate of turning of the spectrum (directional relaxation) hit the middle ground in the intercomparison study. The logic described in Sec. IV.c needs to be modified. Instead of using the local peak frequency (and the wind frequency) to define a frequency border for applying the spectral limiter, we believe it would be worth trying a border that depends on the average wave direction, namely, $f_U = 0.13\, g/(U\cos(\theta_U - \bar{\theta})$ for $|\theta_U - \theta| < 90°$. Comparison of model behavior with observations (and limited theory) is necessary here.

The real test of the model, we believe, would come in an actual hindcasting study. Application of rigorous techniques for comparing model results and data would be very helpful. A key part of such a study would be trying to assign how much of the 'error' might be due to model inadequacies vs. how much might be due to uncertainties in the wind field.

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An improved spectral model for ocean wave prediction is described. The present model, a modified version of the original model by Barnett et al. (contract N62306-68-C-0285, U.S. Naval Oceanographic Office, 1969) includes an improved representation for weak, nonlinear, wave-wave interactions that depends on spectral shape and prescribes atmospheric input that is consistent with measurements by Snyder et al. (J. Fl. Mech. 102, 1-59, 1981). The limiting form of the spectrum is defined as a Pierson-Moskowitz spectrum with

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a variable saturation range parameter. Some additional constraints are also used to obtain stable spectra because there is, in effect, a mismatch between the numerous degrees of freedom of the two-dimensional wave spectrum and the level of sophistication used to represent the physical processes affecting wave growth.

The focus of the present note is on the wave model computer program. The note is organized for someone wanting to implement the program. Hence, top-level flow charts, user instructions, and tape output formats are given. In addition, a detailed description of the numerical method is included.

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